Evaluation of a two-source energy balance model in an advective environment

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Abstract

A two-source energy balance model (TSEB) was evaluated in terms of latent heat flux (LE) for six crops, wheat stubble, and bare soil in an advective environment, and net radiation (R_n) was modeled both with and without separate transfer characteristics used for visible and near-infrared radiation. Observed (i.e., ground-truth) LE was derived from changes in mass measured by precision weighing lysimeters averaged to 0.5-h, and observed R_n was measured by net radiometers at the lysimeters. Agreement between observed and predicted R_n was not greatly influenced by separation of visible and near-infrared radiation, possibly because constant soil albedo was assumed for visible and near-infrared wavelengths. The TSEB tended to overestimate LE for smaller observed LE (< |400| W m^{-2}) by up to 200 W m^{-2}, but relative error improved as observed LE increased and appeared not to be influenced by strong regional advection.

Introduction

Evapotranspiration (ET) estimates of crops and natural vegetation are fundamental for irrigation management and water resources planning at scales from within a field to entire watersheds and regions. Spatially-distributed ET is most conveniently estimated using energy balance models designed to use remotely sensed surface temperature and meteorological parameters. Most energy exchange at the earth's surface involves both the soil and canopy; therefore, energy balance models that account for these two sources separately (termed two-source energy balance, or TSEB) offer better agreement with observations than single-source (e.g., "big leaf") models for partial canopies. Furthermore, two-source models that account for energy exchange between soil and vegetation (i.e., series resistances) provide better results than those where soil and vegetation energy budgets are separate (i.e., parallel resistances) (Kustas and Norman, 1999; Colaizzi et al., 2005).

Norman et al. (1995) and Kustas and Norman (1999) described an operational TSEB model requiring little additional information or assumptions over typical single source models. Their model showed good agreement (i.e., within expected measurement error) with observations over subhumid prairie, semiarid shrub, and fully irrigated crops. Their observations consisted of meteorological-flux stations, eddy correlation, and Bowen ratio systems, which provide reasonable energy balance closure in non-advective conditions. The USDA-ARS Conservation Research Laboratory in Bushland, TX, USA is located in a semiarid environment with strong regional advection from the South and Southwest; consequently, eddy correlation and Bowen ratio systems are subject to errors in energy balance closure (Todd et al., 2000). Evapotranspiration of crops has been measured at this location by four large precision weighing lysimeters under dryland to fully irrigated conditions since 1987. Hence it is an ideal location for evaluating energy balance models for various crops under a wide range of climatic and soil water conditions.

The objective of this paper is to evaluate the TSEB model in an advective environment for crops and other surfaces typical of the Great Plains region of the USA. An additional objective is to compare two methods of estimating net radiation, including simple exponential divergence of radiation to the soil and canopy, and a detailed model described in Chapter 15 of Campbell and Norman (1998) for reflection and transmission of radiation in the visible and near-infrared wavelengths.

Procedure

Evapotranspiration data (converted to latent heat flux) for six crops, bare soil, and wheat stubble was provided by four large precision weighing lysimeters (Marek et al., 1988; Howell et al, 1995a) at the USDA-ARS Conservation Research Laboratory in Bushland, TX, USA (35º 11' N lat., 102º 06' W long., 1,170 m elevation M.S.L.). The climate is semi-arid with a high evaporative demand of about 2,600 mm per year (Class A pan evaporation) and low precipitation averaging 470 mm per year. Each lysimeter is fully instrumented with a micrometeorological station and stationary thermal infrared radiometers (TIR) that view the lysimeter surface at an oblique angle (i.e., pointed toward the Southwest and 60° from nadir). Crops included fully irrigated alfalfa (Evett et al., 2000), fully irrigated corn (Tolk et al., 1995), fully to partially irrigated and dryland cotton (Howell et al., 2004), dryland grain sorghum, fully irrigated soybeans, and fully irrigated winter wheat (Howell et al., 1995b). Although the present study did not use spatially-distributed thermal data, the stationary TIRs provided data coincident with lysimeter and micrometeorology measurements (0.5-hr), so that the TSEB model could be evaluated at different times of the day (±3 hr from solar noon). Observations were limited to clear days when measured incoming solar radiation was similar to theoretical clear sky radiation. Agreement between observed net radiation and latent heat flux and those predicted by the TSEB model was evaluated based on slope, intercept, coefficient of determination (r^2), mean absolute difference (MAD), and root mean squared difference (RMSD). A future version of this paper will include other measures of model performance recommended by Legates and McCabe (1999).

TSEB description

The two-source energy balance (TSEB) model is briefly described as follows. The overall energy balance of the surface is

$$LE = -(R_n + G + H) \tag{1}$$

where LE is the latent energy flux (LE is converted to ET by dividing by the latent heat of vaporization), R_n is the net radiation, G is the soil heat flux, and H is the sensible heat flux. In eq. (1), the sign convention is that all terms are positive toward the surface or ground. The TSEB partitions R_n, H, and LE into canopy and soil components (subscripts *c* and *s*, respectively, throughout this paper; Fig. 1), and G is proportional to $R_{n,s}$. Energy exchange in the soil-canopy-atmosphere continuum is based on series resistances to heat and momentum transport, and H_c and H_s are estimated by the temperature gradient-resistance network in Fig. 1. Canopy and soil temperatures (T_c and T_s, respectively) and all resistances are derived by iterative procedures given in Norman et al. (1995) and Kustas and Norman (1999), which require the brightness temperature measured by a thermal infrared radiometer (TIR) and the proportion of soil and canopy present, among other factors. Norman et al. (1995) and Kustas and Norman (1999) provide all computational procedures for the TSEB used in this paper, and Norman and Becker (1995) present a thorough discussion on terminology used in thermal infrared remote sensing.

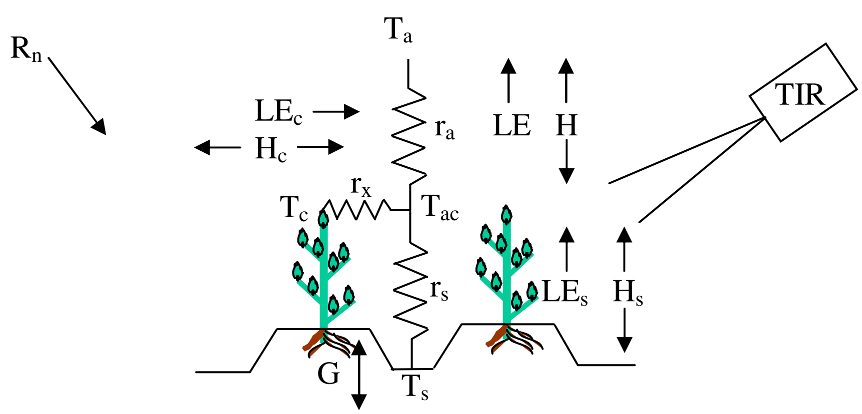

Figure 1. Two source energy balance model (TSEB) with series resistances, adopted from Norman et al. (1995), Fig. 11.

In this paper, R_n was estimated using two different models. In the first model, radiation was partitioned to the canopy and soil fractions using a simple exponential function. The second model used a more detailed approach outlined by Campbell and Norman (1998) that accounts for the different absorption and reflection in the visible and near-infrared wavelengths, as well as longwave radiation contributions from the soil, which can be significant for row crops with sparse canopies and are not accounted for with the exponential function. For exponential partitioning, total R_n was

$$R_n = (1-\alpha_{c-s})R_s + \varepsilon_{atm}\sigma_{sb}T_a^4 - \varepsilon_{c-s}\sigma_{sb}T_{rad}^4 \qquad (2)$$

where α_{c-s} is the bulk albedo of the canopy-soil surface, R_s is the incoming shortwave solar radiation (W m^{-2}), ε_{atm} is atmospheric emissivity, σ_{sb} is the Stephan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T_a is the air temperature (K), ε_{c-s} is the bulk emissivity of the canopy-soil surface (≈ 0.98), and T_{rad} is the ensemble directional radiometric temperature of the surface (K). R_n is then partitioned to the canopy and soil by

$$R_n = R_{n,c} + R_{n,s} \qquad (3)$$

where $R_{n,c}$ and $R_{n,s}$ are net radiation to the canopy and soil surface, respectively (W m^{-2}), and $R_{n,c}$ is

$$R_{n,c} = R_n\left[1-\exp\left(\frac{-\kappa LAI}{\sqrt{2\cos(\phi)}}\right)\right] \qquad (4)$$

where κ is an extinction coefficient ($\kappa = 0.6$; Kustas and Norman, 1999), LAI is leaf area index, φ is the solar zenith angle, and $R_{n,s}$ is given by eq. (3).

For the Campbell and Norman procedure, $R_{n,c}$ and $R_{n,s}$ are separated into shortwave (S) and longwave (L) components by

$$R_{n,c} = S_{n,c} + L_{n,c} \qquad (5a)$$
$$R_{n,s} = S_{n,s} + L_{n,s} \qquad (5b).$$

Longwave components are

$$L_{n,c} = [1-\exp(-\kappa_L \Omega LAI)] \bullet [L_{sky} - L_s - 2L_c] \qquad (6a)$$
$$L_{n,s} = [\exp(-\kappa_L \Omega LAI)]L_{sky} + [1-\exp(-\kappa_L \Omega LAI)]L_c - L_s \qquad (6a)$$

where κ_L is a longwave extinction coefficient ($\kappa_L = 0.95$; Kustas and Norman, 1999), Ω is a clumping factor that accounts for non-random distribution of vegetation (i.e., row crops) and is a function of solar zenith angle, L_{sky} is incoming longwave radiation emitted from the sky (W m^{-2}), L_S is longwave radiation emitted from the soil (W m^{-2}), and L_C is longwave radiation emitted from the canopy (W m^{-2}). L_{sky}, L_S, and L_C are estimated by the Stefan-Boltzmann law. Shortwave components are

$$S_{n,c} = (1-\tau_c)(1-\alpha_c)R_s \quad (7a)$$

$$S_{n,s} = \tau_c(1-\alpha_s)R_s \quad (7b)$$

where τ_c is solar transmittance in the canopy, α_s is soil albedo, and α_c is canopy albedo. Albedo and transmittance are further separated into direct and diffuse shortwave components, both in the visible and near-infrared wavelengths. These are basically functions of soil albedo and leaf absorption in the visible and near-infrared wavelengths, and canopy structure (i.e., leaf distribution, height, clumping, and LAI). Further details are given in Campbell and Norman (1998).

Results and Discussion

Agreement between observed and predicted net radiation (R_n) for the two radiation models are given for alfalfa (Table 1), corn (Table 2), cotton (Table 3), grain sorghum (Table 4), soybeans (Table 5), bare soil (Table 6), winter wheat (Table 7), and wheat stubble (Table 8). Model results are termed "simple" where net radiation was partitioned between the soil and canopy using the simple exponential function (eq. 4), and "CN98" using the procedure outlined by Campbell and Norman (1998). In each table, R_n model results are followed by those for latent heat flux (LE), where LE model results are also termed "simple" or "CN98" depending on which R_n model was used. In Table 6 (bare soil), only the simple R_n model was used because the CN98 model requires a canopy.

The simple and CN98 models resulted in similar prediction of total R_n for all surfaces; however, energy partitioning to the soil and canopy components were different for each model (data not shown), and the CN98 model tended to have slightly greater bias. In Tables 1-8, the mean absolute differences (MAD) and root mean squared differences (RMSD) between observed and predicted R_n were slightly greater using CN98 than the simple model for all surfaces except winter wheat and wheat stubble, where soil cover was more complete for observed days. The CN98 model may have been limited in its ability to predict R_n by the lack of real-time soil albedo (α_s) measurements, which can vary greatly within a few hours during soil surface drying (Evett, 2002). Instead, we assumed constant $\alpha_s = 0.13$ (visible) and $\alpha_s = 0.25$ (near-infrared), which were average values measured over (mostly dry) bare soil. The CN98 model will nonetheless continue to be evaluated in future studies where reflectance is measured.

Agreement between observed and predicted LE was not greatly influenced by choice of R_n model (Tables 1-5, 7, 8). For all surfaces except bare soil, LE tended to be overestimated for smaller ($< |400|$ W m^{-2}) LE observations using the simple model (Fig. 2) as well as the CN98 model (*xy*-plots not shown). This appeared to be related to over-partitioning available energy to LE (instead of H) for partial canopies, which in turn may have resulted from model formulations, or bias from the relatively small TIR measurement area. The RMSD ranged from 77.4 W m^{-2} to 153.2 W m^{-2} (Tables 1-8), which were much greater than those reported by Norman et al. (1995) and Kustas and Norman (1999), who used coarser-resolution airborne radiometer data and transects of ground-based TIR measurements, and different instrumentation to observe LE (i.e, meteorological-flux stations, eddy correlation, and Bowen ratio systems). In the present study, all slopes (predicted vs. observed LE) were significantly less than one and ranged from 0.62 to 0.94. All intercepts (except for bare soil) were significantly less than zero and ranged from -4.12 to -172.75 W m^{-2}. Error was relatively small for larger observed LE, which included days of strong regional advection; however, LE was under-estimated by about 100 W m^{-2} for winter wheat when advection occurred.

Conclusion

Total net radiation (R_n) prediction was similar for six crops, wheat stubble, and bare soil using either a simple exponential function or a detailed model described by Campbell and Norman (1998); however, the Campbell and Norman model often resulted in greater bias, which may have been related to assuming constant soil albedo. This will be addressed in future studies by using spatially-distributed measurements of reflectance to better characterize albedo. The choice of the R_n model did not greatly influence agreement between observed and predicted latent heat flux (LE) using the two-source energy balance (TSEB) model. For all surfaces except bare soil, the TSEB tended to overestimate latent heat flux (LE) for observed LE < |400| W m^{-2}. This appeared related to over-partitioning available energy to LE for partial canopies, which in turn may be related to model formulations, or the relatively small thermal-infrared radiometer (TIR) measurement area. Future studies at out location will include TIR transects and coarser-resolution airborne and satellite data. The TSEB model generally appeared to account for advected energy because the relative error of predicted vs. observed LE improved as observed LE increased for all surfaces except winter wheat.

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Table 1. Model results for alfalfa (n = 5221).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	436.9	443.3	0.98	13.56	0.95	10.8	35.6
CN98	R_n	436.9	471.3	1.08	0.43	0.94	18.8	53.5
Simple	LE	-296.2	-331.3	0.88	-71.84	0.86	33.8	91.3
CN98	LE	-296.2	-339.5	0.87	-83.30	0.87	35.3	92.0

Table 2. Model results for corn (n = 980).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	511.8	512.9	1.02	-6.92	0.94	20.8	28.8
CN98	R_n	511.8	533.7	1.04	1.62	0.94	32.3	38.1
Simple	LE	-258.6	-279.0	0.92	-41.09	0.81	67.0	83.2
CN98	LE	-258.6	-277.6	0.91	-42.57	0.80	67.1	84.2

Table 3. Model results for cotton (n = 3696).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	581.9	495.6	0.96	-64.11	0.95	50.5	90.1
CN98	R_n	581.9	486.8	0.83	4.73	0.92	55.2	101.5
Simple	LE	-203.1	-266.6	0.75	-113.45	0.57	72.1	117.5
CN98	LE	-203.1	-250.3	0.67	-113.75	0.50	69.7	115.6

[a] Simple: Net radiation is partitioned to the soil and canopy using a simple exponential function.

CN98: Net radiation is partitioned to the soil and canopy using a model from Campbell and Norman (1998), where canopy albedo and transmissivity are partitioned for direct and diffuse radiation both in the visible and near-infrared spectral regions.

[b] $\overline{O_i}$: Observed mean.

[c] $\overline{P_i}$: Predicted mean.

[d] Slope of least squares regression: $\overline{P_i} = a + b(O_i)$.

[e] Intercept of least squares regression: $\overline{P_i} = a + b(O_i)$.

[f] r^2: Coefficient of determination.

[g] Mean absolute difference: $MAD = \sum_{i=1}^{n} \left| P_i - O_i \right| / n$.

[h] Root mean square difference: $RMSD = \sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n}$.

Table 4. Model results for grain sorghum (n = 1778).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	524.5	524.8	0.94	30.68	0.93	21.3	30.3
CN98	R_n	524.5	521.5	0.85	73.44	0.90	26.5	38.0
Simple	LE	-293.3	-309.4	0.69	-106.80	0.60	78.5	97.2
CN98	LE	-293.3	-289.3	0.62	-107.42	0.53	80.8	103.7

Table 5. Model results for soybeans (n = 1274).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	591.8	516.9	0.94	-38.41	0.90	75.0	84.9
CN98	R_n	591.8	510.1	0.81	27.75	0.84	82.0	95.6
Simple	LE	-261.9	-291.1	0.92	-49.41	0.88	63.2	77.4
CN98	LE	-261.9	-274.4	0.85	-52.98	0.84	66.6	82.1

Table 6. Model results for bare soil (n = 644).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	517.1	520.3	0.96	26.17	0.91	23.2	27.7
CN98	R_n	----	----	----	----	----	----	----
Simple	LE	-108.8	-106.3	0.94	-4.12	0.49	63.1	78.8
CN98	LE	----	----	----	----	----	----	----

Table 7. Model results for winter wheat (n = 1176).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	480.9	450.2	0.88	27.49	0.92	44.3	56.4
CN98	R_n	480.9	465.4	0.89	37.08	0.93	36.4	46.8
Simple	LE	-237.0	-320.7	0.70	-154.12	0.73	107.0	135.7
CN98	LE	-237.0	-327.4	0.65	-172.75	0.72	110.6	141.7

Table 8. Model results for wheat stubble (n = 518).

Model[a]	Parameter	$\overline{O_i}$ [b] W m^{-2}	$\overline{P_i}$ [c] W m^{-2}	Slope[d]	Int.[e] W m^{-2}	r^2 [f]	MAD[g] W m^{-2}	RMSD[h] W m^{-2}
Simple	R_n	378.6	359.7	0.79	59.75	0.93	28.1	35.8
CN98	R_n	378.6	376.8	0.86	51.99	0.93	17.4	27.6
Simple	LE	-37.9	-165.7	0.66	-140.68	0.28	127.8	132.4
CN98	LE	-37.9	-186.2	0.75	-157.60	0.28	148.3	153.2

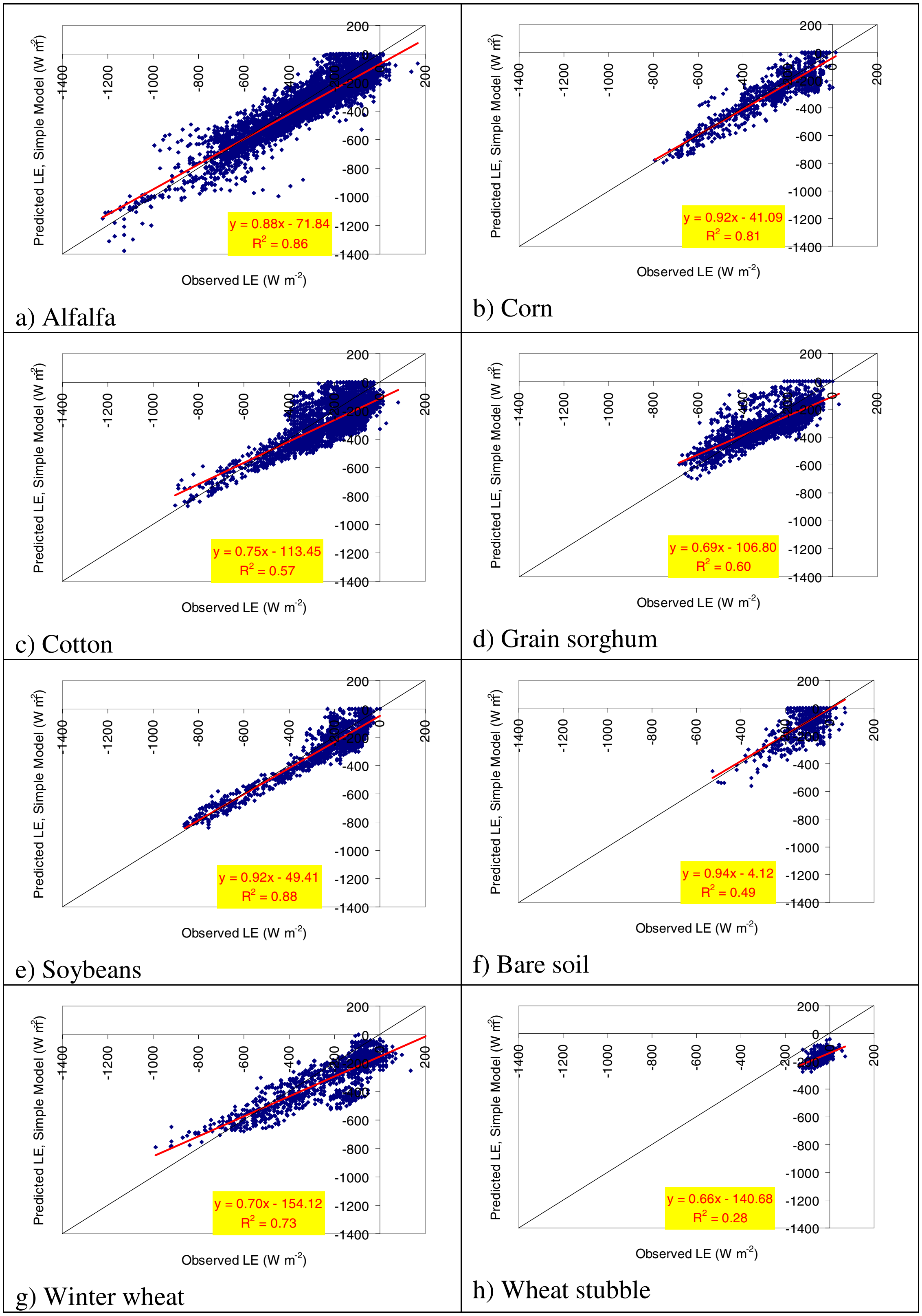

Figure 2. Predicted vs. observed latent heat flux (LE) for eight surfaces at Bushland, TX, where net radiation is partitioned using a simple exponential function.